Cosmic Ray Equilibrium* NsG-386

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UNPUBLISHED PRELIMINARY DATA

As is well known, particle acceleration mechanisms which operate so that rate of energy gain is proportional to energy lead to a cosmic ray energy spectrum that is, for high energies at least, a power law. In particular, as was shown by Fermi, if the energy gain is described by $dE/dt = \alpha E$ and T is a characteristic time for catostrophic loss (or leakage), the resulting energy spectrum is of the form $KE^{-\gamma}dE$ with $\gamma = 1 + (\alpha T)^{-1}$. In any proposed model for which α, T and the cosmic ray energy density are unrelated physically, the exponent γ can in principle have a wide range of values for different astronomical systems. (In such models there is, in fact, nothing to prohibit values of $\gamma \leq 2$ for which the energy content would be infinite.) On the other hand, radio noise from a large variety of astronomical systems, interpreted as synchrotron radiation by electrons made in heavy particle (proton) collision processes, indicates that radio spectral indices and therefore the related exponent of the proton energy spectra have but relatively narrow ranges of values.

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A. The Proton Spectrum

For the reasons stated above, we have been led to consider a model wherein the characteristic leakage time T is determined by the proton component itself. Imagine, for example, a region of space in which a magnetic field of mean energy density $U_B = B^2/8\pi$ and an acceleration mechanism characterized by α exists. Then when particles are injected at low energy, say from super novae or stellar flares, we assume that the particle energy density, U_p, will build up until the particle pressure begins to distort the confining magnetic field. This distortion presumably does not become appreciable until $U_p \approx U_B$, and we assume has the effect of reducing the leakage time T in such a way that the approximate equality of U_p and U_B is maintained*. Under these conditions, if we ignore ionization energy losses, we have

$$\int N \alpha \, E dE + \int qE' dE' = \frac{1}{T} \int NE dE .$$

Here N is the density of protons of E in dE and q is the density of protons of E' in dE' injected per second. This reduces to

$$\gamma = 2 + Q\,(\alpha U)^{-1}$$

where $U = \int NEdE$ is the proton energy density and $Q = \int qE'dE'$ is the

* (In this connection it is interesting to note that while the magnetic field arising from a completely isotropic cosmic ray flux is negligible, that arising from even a very small anisotropy can be relatively large and in effective control of the interstellar field.)

average energy injected per unit volume per second. It is clear that γ, when in the observed range from 2 to 3, is only very weakly dependent upon Q, α and U. Any model which postulates a feedback mechanism and envokes energy conservation will predict a similar weak dependence of γ upon astrophysical quantities.

B. Electrons

A portion of the galactic electron component must certainly arise via meson decay from proton-interstellar gas collisions. Another portion may arise from direct acceleration in super novae. We wish, here, to examine briefly the question of interstellar acceleration by mechanisms of the sort postulated in part A.

As is well known, electrons are difficult to accelerate because with their small mass (recall that E in $dE/dt = \alpha E$ is total energy) energy losses via collision and bremsstrahlung processes are relatively more important. Even if α is large enough to make the net dE/dt positive in some energy region, there must certainly be an energy E_o at which dE/dt becomes zero because the magnetic bremsstrahlung losses increase as E^2. Certainly no electrons can be accelerated to energies greater than E_o, and the question arises as to the spectral form of those directly accelerated electrons having $E < E_o$.

Near E_o magnetic bremsstrahlung losses will dominate and we have

$$Z = \frac{dE}{dt} = \alpha E - bE^2$$

where b depends upon the magnetic field. Since $Z = 0$ when $E = E_o = \alpha/b$, $Z \approx \alpha\,(E_o - E)$. If electrons are injected at some energy E_1, the equilibrium number at a higher energy E is

$$N \sim \frac{1}{Z}\, e^{-t/T}$$

where $t = \int_{E_1}^{E} \frac{dE}{Z}$ is the time for the electron to drift from energy E_1 to energy E. The spectral form is then

$$N \sim (E_o - E)^{\gamma - 2}$$

where $\gamma = 1 + (\alpha T)^{-1}$. Since γ must be 2 or greater, N tends to remain relatively constant out to E_o, at least when compared to a power law spectrum. It is clear that the radio emission which would result from a mixture of these electrons with those from meson decay will have a spectral index smaller than that from the meson decay electrons alone.

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